POOR SURFACES AND INTERSECTIONS OF SURFACES STILL CAUSE TROUBLE JUST LIKE THEY USED TO DO

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Abstract: For nearly half a century engineering designers, materials engineers, and metallurgists have known that poorly machined surfaces and sharp "inside" corners lead to cracking, fatigue, and disastrous failures. Yet, products with these types of deficiencies continue to be produced, having been designed with what is intended to be an ample design factor to avert a potential problem. So often, these products fail. In this paper, we will discuss the effects of surface finish and corner radii on product durability, and provide photographic examples to illustrate the types of failures that occur due to deficient conditions. These failures are well known to failure analysts and engineers in manufacturing, but are worth reviewing here. We will then challenge engineers to specify and inspect for surface finish and fillet radius requirements for their products.

Key Words: Fatigue; fracture; notch; sharp radius; stress concentration; stress raiser; surface finish.

INTRODUCTION: Deficiencies of surfaces and surface intersections cause so many product failures that it is worthwhile pointing out again what the problems are and then issuing a "call" that product designers and materials engineers enumerate surface finish and fillet radius requirements and that quality control departments inspect for compliance with those requirements. Current engineering practice generally is to specify alloy grade, material composition and mechanical properties very carefully. Only if surface finish and radii of intersections are considered critical are they also specified. Then, during manufacturing, the alloy grade, composition, and mechanical properties are usually checked by quality control; but the surface finish and radii are frequently not checked. There may be a lack of appreciation by product designers of the deleterious effect that inadequate radii at intersections and poor surface finish can have on product life.

The types of situations that cause failures are well known to failure analysts and materials engineers in manufacturing. They are published in many books. Several examples are given

here, not to illustrate the method of failure analysis, but simply to be a refresher. We don't give alloy compositions, heat treatments, and service conditions because we want to lessen attention on the failure analysis and increase attention on the problem.

STRESS RAISERS: A sharp radius at the intersection of surfaces and a rough surface finish are two examples of stress raisers, or "stress concentrations." Any geometrical discontinuity in a stressed solid, such as a notch, a spline, a keyway, or a hole, results in an increase in the stress at the discontinuity above the average stress away from this feature [1].

Detailed data showing the effects of stress raisers on the local stresses at discontinuities are well documented by Peterson [2]. The data are presented in the form of stress concentration factors (K_t) for many different geometrical discontinuities stressed in different ways. The stress concentration factor is the ratio of the maximum stress to the nominal stress at the discontinuity. The stress concentration factor generally increases with *increasing* depth and *decreasing* radius at the discontinuity. A rough surface finish, therefore, can result in a high stress concentration factor since the many discontinuities (i.e. "peaks and valleys") at the surface have small radii. Similarly, widely used features in machinery components such as the geometrical discontinuities described above are also stress raisers on a larger scale.

High stress concentrations can affect the performance of products in different ways. If a component is loaded statically or sustains a single load application at a magnitude that exceeds the capability of the material, a crack initiates and propagates (often rapidly) from the stress concentration site. If the static load is constant and well below the yield strength, while the component is exposed to an aggressive environment, the sustained stress is increased at the discontinuity and a failure mode known as stress corrosion cracking [3] can initiate at the stress raiser.

If fluctuating or cyclic loads are applied to the component, the presence of stress raisers reduce the fatigue life of the component. The degree to which rough surfaces affect the lives of components is accounted for in one of the fatigue strength modifying factors known as the "surface factor" [4]. This factor, a fraction less than one, is applied to the fatigue strength obtained with laboratory specimens which have been carefully machined and polished. The factor depends on the surface finish, produced by such processes as grinding, machining, chemical machining or etching, hot rolling, forging or casting, and on the tensile strength of the material.

Sharp radii at the intersections of surfaces also affect fatigue properties. The reduction in fatigue strength due to the presence of a sharp radius is known as the fatigue-notch factor, K_f. This factor varies with the severity and type of the notch, the tensile strength of the material, the type of loading, and the stress level [5].

The impact of surface discontinuities must be considered for both static *and* cyclic load conditions. Under some circumstances, such as for rotating shafts with keyways, the nominal stress through the cross section of the component at the discontinuity may be low, but the

reduction in fatigue strength may be very high, due to a high K_f, which could result in premature failure.

CASE HISTORIES: First, a trunion shaft approximately 4" diameter that failed in fatigue starting from origins on the inner surface. Figure 1 shows the fracture with two arrows pointing to origins on the rubbed (post fracture) surface. Figure 2 shows the step-like fracture progression so typical of fatigue, and Figure 3, with an arrow pointing to a tiny crack just starting, shows the roughly machined inner surface in which the origins were found. Surfaces machined inadequately for the service that the component must endure are a major source of failures of load-bearing and rotating components. Poor surface preparation can include simple roughness, tears, gouges, and chatter.

Another example of poor surface is in Figures 4 and 5. Thread rolling laps caused nuts to be loosely tightened on bolts; and the looseness ultimately allowed vibration and fatigue failure. The looseness was due to surface finish of threads: slivers (laps) of steel were able to tear free from the rolled threads during tightening and cause galling between nuts and bolts. This led to the nuts appearing to be adequately fastened when actually they were not.

Sharp radii where surfaces intersect in keyways or where diameters change on rotating shafts are so commonly understood as a problem that they should not have to be discussed in modern times by materials engineers and designers. Yet, the problem is still major and causes serious financial losses in downtime and repairs for some manufacturers. Figure 6 shows a crack emanating from a sharp corner in a keyway of a huge printing press roll. When the other end of this roll, made the same way, failed catastrophically, the total loss was in the millions of dollars. Figure 7 shows this fracture opened to reveal the fracture origin (arrow) at this sharp corner. Here, a single overload at the sharp corner caused a rapid brittle fracture.

Poorly ground surfaces may contribute to fractures, as shown in Figures 8, 9, and 10. This shaft, about 6" diameter and 30' long from a drinking water delivery system also failed in a brittle fashion from the sharp inside corner (origin of crack) in a keyway. The inner surface of the keyway showed considerable grinding "chatter" and checking in the vicinity of the origin revealed additional cracking starting along a machining mark, as Figure 11 shows. Thus, the poor surface may have added to the stress concentration at the keyway corner.

Surface finish anomalies can occur due to processes other than machining. Chemical etching was performed on .004" thick strips, to facilitate bonding to a high frequency resonator. Etching produced many tiny transverse grooves on the strips. When the components were installed in service, the cyclic loads sustained during resonating caused fatigue cracks to initiate and propagate from these surface anomalies, as shown in Figure 12.

The important point is that these failures are recent. They occurred in modern products. Despite the ready availability of knowledge, designers and manufacturers are making stress concentrating mistakes. These failures could all have been avoided by proper specification of surface finishes and radii by the designers, and by quality control use of surface finish and radius measuring devices.

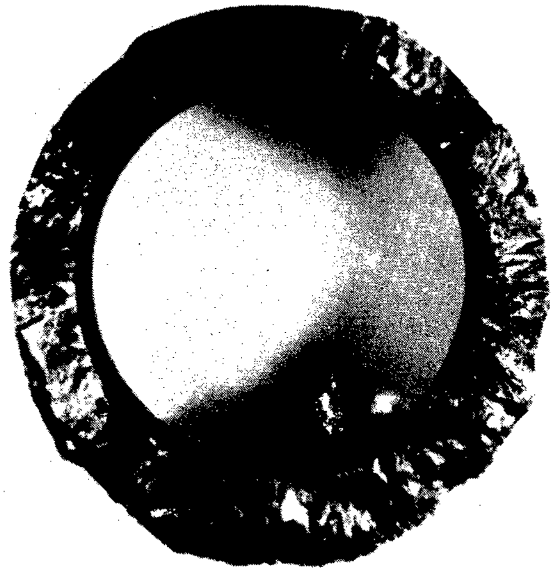

Figure 1. Fracture of 4″ trunion. Mag: 0.6x

Figure 2. Fatigue striations from one origin. Mag: 42x

Figure 3. Crack (arrow) starting in machining groove. Mag: 85x

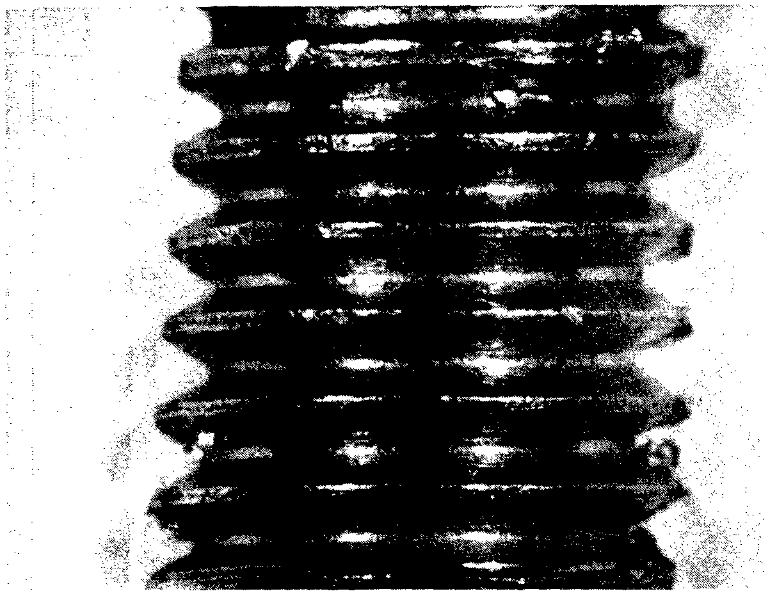

Figure 4. Rolled threads on bolt. Arrows mark defects. Mag: 8x

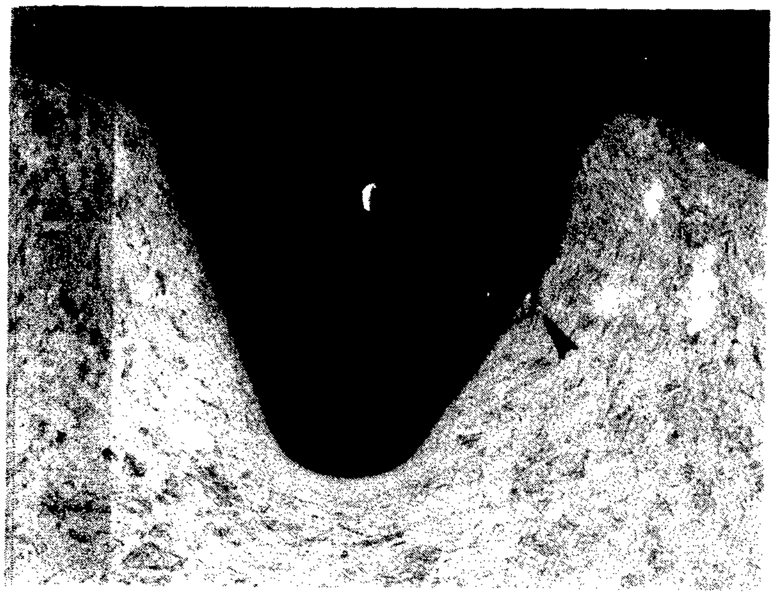

Figure 5. Cross section shows lap re-entering surface. Mag: 64x

Figure 6. Sharp corner. Mag: 1.2x

Figure 7. Arrow shows fracture origin at corner of keyway. Mag: 1.2x

Figure 8. Arrow shows fracture origin at corner of keyway. Mag: 0.4x

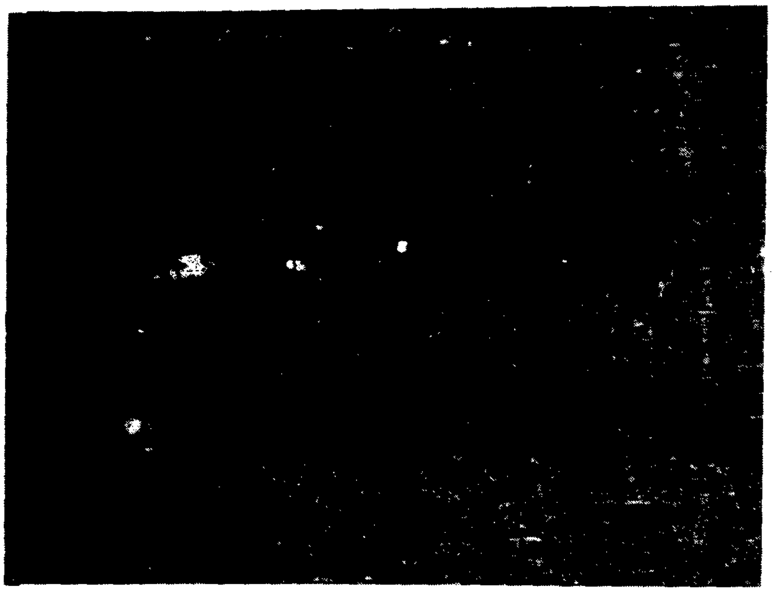

Figure 9. Grinding checks (the vertical pattern) on keyway surface near origin. Mag: 16x

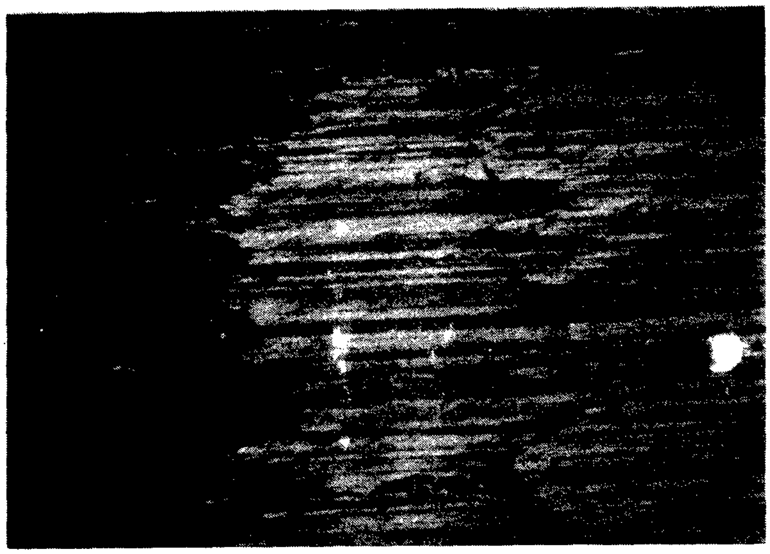

Figure 10. The grinding checks (arrows) in detail. Horizontal pattern is grinding grooves. Mag: 500x

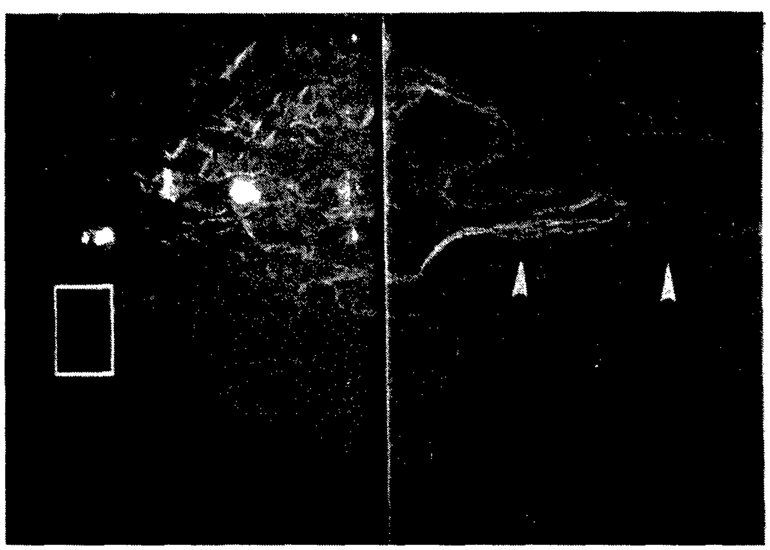

Figure 11. Box at left shows edge of fracture (upper) and keyway surface (lower). Mag: 50x At right: higher magnification view of area in box at edge of fracture, crack (arrow) starts at machining mark . Mag: 400x

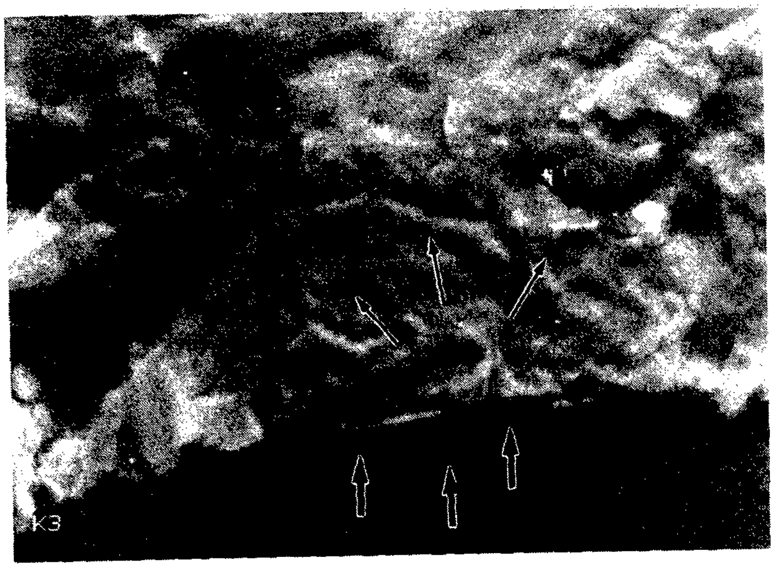

Figure 12. Fatigue crack (small arrows) initiated at groove on surface. Other grooves indicated by large arrows. Mag: 2500×

What should be done? Ultimately, manufacturing standards for most mechanical components, not just the critical ones, must include criteria for surface finish and radii at intersections of planes. Interestingly, ASTM seems to have no standards that relate to the subject and ANSI has only one.

FUTURE EFFORTS: To convince ourselves of the importance of this subject, statistics from failure analysis laboratories all over the country should be gathered, just as the United States Consumer Products Safety Commission gathers statistics on causes of accidents from hospitals. (The Commission uses this data as a basis for issuing product regulations.) To start, requests to review three years' analyses could be issued to two dozen well-qualified independent failure analysis laboratories. They would be asked to determine percentages of failures of mechanical components attributable to stress concentration, surface finish, and radii. This should not be a major undertaking.

The results would indicate if there is a need to survey many more laboratories in a comprehensive study. If the statistics show that poorly fabricated surfaces and intersections are causes of failures, there would be a strong impetus to governmental agencies and manufacturers to find ways to overcome the problem. Specifications would certainly be part of the answer.

CONCLUSIONS: Attention to often overlooked details such as surface finish and radii at the product design stage, as well as during manufacture can significantly improve the durability and performance of products. These features should be specified for critical and noncritical components alike. Development and implementation of specifications defining surface finish and radius requirements for machinery components would generalize the requirements for different configurations, applications, loading conditions, and operating environments. Adherence to these requirements would prevent many failures caused by such discontinuities. There should be a study of failure analysis histories to compile our collective experience with stress concentrations and causes of failures.

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